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Burning Characteristics of Combat Ship Compartments and Vertical Fire Spread

Daniel Gross and William D. Davis

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
(Formerly National Bureau of Standards)
National Engineering Laboratory
Center for Fire Research
Gaithersburg, MD 20899

December 1988

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BURNING CHARACTERISTICS OF COMBAT SHIP COMPARTMENTS AND VERTICAL FIRE SPREAD

D. Gross and W. Davis

ABSTRACT

This is a report to sponsor summarizing work accomplished under Naval Research Laboratory Contract N0017388WR80284 "Burning Characteristics of Combat Ship Compartments and Vertical Fire Spread." The computer program FIRST was employed to estimate levels of temperature, energy and heat transfer in burning compartments having features typical of Naval vessels with emphasis on vertical fire spread due to heat transfer through metal decks.

Key words: Aluminum deck; computer modeling; FIRST; missile propellant; self-ignition; steel deck; vertical fire spread.

1. INTRODUCTION

This study complements the program at NRL to study fire growth in combat ship compartments with emphasis on vertical fire spread as a result of heat transfer through metal decks. Inasmuch as a large number of parameters (geometrical, combustion, thermal and fluid flow) affect the fire growth process, a parametric study using an advanced computer model will help define those parameters which have the greatest impact on the vertical transfer of heat.

The approach selected in this study is to employ the computer program FIRST to estimate levels of temperature, energy, and heat transfer in a burning compartment as a function of compartment size, vent size, combustible load, and compartment enclosure materials. The ranges of values to be explored are intended to cover: the smallest shipboard or experimental mockup spaces as well as large areas likely to be separated by steel watertight compartmentation; openings representing a single hatchway as well as a large combat-produced vent; typical uninsulated steel and aluminum decks and bulkheads as well as composite insulated structures; and combustible contents over the range likely to be found aboard Naval ships. In addition, the presence of an energy source simulating the burning of ordnance weapon propellant will be investigated.

2. COMPUTER MODEL

The computer model FIRST is a comprehensive, deterministic, single-compartment zone fire model which provides a solution of the time-dependent mass and energy

transfer processes in a compartment [1]. The model utilizes heat, mass and momentum balances to determine the conditions within a compartment defined by: one or more burning objects; flames and thermal plumes; a hot upper layer and a cool lower layer; vents or openings in the compartment; enclosing surfaces; and objects of interest exposed to the heating effects in the compartment. The model computes the heat absorbed by the compartment surfaces (by radiation and convection) and also computes the heat transferred by conduction and then lost (by radiation and convection) from the outside surface of the compartment "walls".

While FIRST is a fairly comprehensive model, its basic features and limitations need to be kept in mind. For example, this two-zone model requires that the ceiling and upper walls be considered as a single uniform temperature surface. Similarly, the floor and lower walls are considered to be another isothermal surface. The combustion, heat transfer, and fluid flow processes generally use single-value coefficients which are preset to best-known values but which may be modified by the user.

The computer model used here is designated FIRST6XX and contains the following enhancements that are relevant to this study but which are not found in the published version:

1. The numerics have been improved by changing the extrapolation technique in the Gauss-Seidel solver and by modifying the subroutine which calculates the pressure in the compartment.

2. An output file PLOT was added to provide a list of output variables relevant to this study. This includes the heat flux emitted from the outside surface of the wall.

3. A wall heat conduction algorithm capable of handling thermally thin walls was added.

4. Floor heating was included in the computation.

In addition to the above changes, a new wall heat conduction algorithm capable of handling walls with up to three independent segments was developed and may be imbedded into the code.

3. PARAMETERS

The principal parameters and corresponding ranges examined in this study were as follows:

PARAMETER	RANGE	
Size of Compartment (m)	2.5W by 2.5D by 2.5H	to 12W by 15D by 3H
Size of Vent (m)	0.65W by 1.65H	to 8W by 3H
Enclosure Material	Steel; Aluminum; Insulated metal	
Combustible Contents (kg/m^2)	10	to 50
(kg)	200	to 5000
Propellant Energy (MJ)	100	to 1000
Heat Transfer Coefficient (W/m^2K)	1	to 50
Initial Burning Radius (m)	0.1	to 1
Maximum Burning Radius (m)	1.25	to 7.5

Parameters which may be specified for each run from a menu but which were not systematically varied included the following (selected or default values in parentheses):

	Plume Model	(Morton-Taylor-Turner area source)
	Initial Compartment Temperature	(300 K)
	Ambient (exterior) Temperature	(300 K)
	Specific Heat of Air	(1004 J/kg K)
	Heat Transfer Coefficient (Objects)	(10 W/m^2 K)
	Plume Entrainment Coefficient	(0.1)
	Vent Flow Coefficient	(0.68)
Burning <u>Object</u>	Position/Orientation	(Center of floor/horizontal)
	Material	(Flexible Urethane Foam)
	Heat of Combustion	(28.7 MJ/kg)
	Fraction of Heat Released	(0.65)
	Pyrolysis Temperature	(600 K)
	Ignition Temperature	(770 K)
	Stoichiometric (Air/Fuel) Mass Ratio	(9.85)
	Emissivity/Absorptivity	(0.98)
	Fire Spread Parameter	(0.0137 m/s)
	Burnout Parameter	(20 s)
	Flame Extinction Coefficient	(1.28 m^{-1})
<u>Vent</u>	Transom Depth	(0 m)
	Forced Ventilation	(absent)

4. MATERIALS

The materials comprising the enclosure surfaces are listed in Table 1 along with the assumed thermal properties corresponding to reference source room temperature values. In view of the possible magnitude of other uncertainties, variations of these properties with temperature and differences in surface absorptivity (emissivity) are not taken into account in this model. Also listed are the assumed properties of two of the most common contents likely to be found in Naval vessel berthing compartments and electronic spaces. Different types of electrical cables may be found aboard Naval vessels. The thermal and

combustion characteristics selected for this preliminary study approximated a "cable" composed entirely of PVC since the insulation may constitute 50 % or more of the total cable weight and since PVC-jacketed cable is among the most prone to undergo insulation degradation and ignition in laboratory tests [2].

5. FIRE INITIATION

Accidental fires are a fact of life in all types of occupancies where there is human activity and energy usage. Aboard Naval vessels, especially in battle-ready conditions, weapons-initiated fires are also anticipated. Two main types of fire initiation have been considered here:

(a) a localized ignition resulting in a fire which spreads relatively slowly on combustible contents (i.e., non-battle conditions)

(b) a distributed ignition arising from the action of an ordnance weapon including the burning of propellant (i.e., battle conditions).

In the former case, a typical fire ignition was taken to consist of a 0.1 m radius fire spreading on an extended horizontal combustible surface at deck level. This was intended to simulate distributed combustibles in berthing spaces and a single slab representing flexible urethane mattresses was used for convenience to represent all combustible contents. In the latter case, ignition was assumed to be the very rapid release of energy corresponding to the burning of 137 kg (300 lb) of a mixture of polymer, aluminum and ammonium perchlorate based on an estimate from the final report on damage assessment and analysis [3]. Assuming the propellant burns in a berthing compartment after the contents have been re-distributed on missile entry, the initial radius of the fire could be considerably larger. For the selected fire spread parameter and combustible load in the largest compartment, there is a time delay of less than 5 minutes in reaching the fully involved burning stage if the initial burning radius is 0.1 rather than 1.0 m.

The propellant energy release was modelled as a gas burner with an artificially high heat of combustion (50×10^{8} J/kg) and correspondingly low mass burning rate (0.007 kg/s maximum). Since missile propellants carry their own oxygen, this scheme avoided unrealistic oxygen depletion from the compartment air supply, the conditions associated with the diffusive burning mode assumed in the model. However, no allowance was made for the increase in product mass resulting from propellant burning.

6. CRITERIA

Fire spread between compartments may occur horizontally or vertically according to several likely modes:

- o Direct flame impingement through openings
- o Hot gas convection and/or radiation through openings
- o Hot surface ignition of combustible contents due to wall heat conduction

- o Heated air ignition of combustible contents ("oven" or "self-heating" effect)

In the absence of hatches, scuttles or other penetrations in metal decks, the first two spread modes are excluded. Vertical fire spread is here assumed to occur only under the following conditions and criteria:

(a) Aluminum deck temperature exceeds 400°C (752°F)
This corresponds to a slightly lower temperature than the melting point of aluminum alloys (approx. 600°C) but makes allowance for the significant loss of yield strength at temperatures above 250°C which could result in local punctures at points of load concentration. Less than 25 percent of the yield strength of aluminum alloys remains at 400°C.

(b) Hot surface ignition of combustibles above the heated deck
Very little published experimental data exist on the non-piloted ignition of solid material layers on hot surfaces. Table 2 lists approximate ignition temperatures, estimated from available sources [4,5,6], that are intended to represent self-ignition of thick (≥0.2 m) or well-insulated layers above an extended hot surface.

(c) Excessive air temperature in adjoining compartment
This corresponds to a temperature at which self-heating of certain stored combustibles may occur in the absence of a flame, spark or other ignition source. Such "self-ignition temperatures" depend greatly upon size; geometry; exposure duration; and material property kinetics [4,5]. Very approximate estimates of exposure temperatures and times based on available information on self-ignition behavior are also listed in Table 2. The actual time period required for transition from a self-sustained smoldering reaction ("ignition") to open flame is very uncertain.

7. RESULTS

A summary of critical outputs from selected computer simulation runs is given in Table 3. The emphasis has been placed on the temperatures and levels of heat flux penetrating the ceiling (deck) and upper wall. It should be kept in mind that the actual magnitudes of temperature and of energy and mass flow rates depend upon the model assumptions and the selected constants, the combined effects of which may be considerable. For example, the specified maximum size (radius) of the burning item has a very large effect on the burning (mass loss) rate, even in compartments with a limited size vent. Also critical are the entrainment coefficient, the spread rate parameter, and the plume model selected.

In this study, estimates are provided over a very wide range of conditions, including combinations of conditions not originally considered in the FIRST code. In particular, there has been very limited experimental validation of model predictions for large area compartments, small vents, conductive walls and spreading fires.

Based on the tabulated data in Table 3 for the available runs, the following may be noted:

- o Energy Release

  The actual energy release rate in a ventilation-limited compartment fire may be significantly less than that computed from the product of mass burning rate and effective heat of combustion. This computer model prediction is based on recognition that burning will not be complete within an oxygen-limited compartment and that partially decomposed products will vent from the compartment and burn outside. In this series of simulated runs, the portion of the available energy which is actually released in the fire compartment ranged from 1.5 to 100 percent. The lowest value corresponds to the most restricted ventilation condition, i.e., the largest compartment with smallest vent and highest combustible load (Run 66); the highest value corresponds to a compartment with a large vent relative to its size and combustible load (Runs 61A and 65A). Graphical data from a typical computation (Run 61A) is shown in Figure 1(A-F).

- o Vent Size

  For a given size steel compartment, increasing the vent size permits burning of combustibles to be more rapid and complete, whereas decreasing the vent size results in oxygen starvation and incomplete burning. For example, in a 12 by 15 by 3 m (approx 40 by 50 by 10 ft) compartment with a 8 by 3 m (26 by 10 ft) vent and containing 5000 kg (11000 lb) of combustible contents (Run 42B), the upper layer compartment temperature was over 100 degrees C higher than that in the same compartment with a 50 % smaller vent (See Figure 2).

- o Missile Propellant

  The addition of burning missile propellant (1000 MJ) under the same conditions produced a rapid peak temperature of 1065°C (1338°K) after 20 sec, followed by a gradual recovery to a secondary peak temperature of 863°C (1136°K) after 100 sec for the larger vent (Run 49C). Reducing the vent area by factors of 2 (Runs 59, 55 and 66) gave the same rapid peak temperature after 20 seconds (since oxygen depletion was not a factor) but significantly lower compartment temperatures during burning of the contents where oxygen depletion was a factor. The effects are shown graphically in Figure 3 (upper layer-temperature) and Figure 4 (energy output from contents).

- o Small Compartment

  For a small experimental steel compartment (2.5 by 2.5 by 2.5 m) with a hatch-size opening (0.65 by 1.65 m) and a combustible load of 200 kg (urethane), the maximum rate of heat release may reach about 1.8 MW and the computed layer temperature approximately 850°C (1123°K).

- Heat Conduction

  Considerable heat is conducted through uninsulated compartment walls made of 9.4 mm (3/8 in) steel or 6.3 mm (1/4 in) aluminum. The energy conducted through a 12 by 15 m steel deck amounted to approximately 20 % of the total energy released in a 12 by 15 by 3 m compartment with large vent (Run 42B). For comparable test conditions, the aluminum compartment surface heated considerably quicker than the steel and slightly more heat was conducted through it. For an aluminum deck, excessive temperatures sufficient to cause extensive melting would occur after 4 minutes in the large compartment (Run 56) but no melting would occur in a smaller compartment (Run 48B). However, it is possible that local punctures could occur in the smaller compartment since wall temperatures reached 440°C. For an uninsulated steel (or aluminum) deck covered with combustibles, hot surface ignition of typical combustibles could occur in time periods as short as 4 minutes based on the sizes, geometries and combustible loads assumed here. For a compartment of the same volume directly above the fire-involved compartment, self-ignition of insulated cables or stored combustibles could occur within 5 minutes in Run 65A and after approximately one hour in Run 59 (See Table 4).

- Insulation

  The addition of a ceramic fiber insulation layer 25 mm (1 in) thick. would prevent appreciable heat conduction through the metal deck (or bulkhead) but would increase the compartment temperature approximately 500 degrees C (See Figure 5).

- Water Application

  In a typical case of active burning in the large (12 by 15 by 3 m) compartment (Run 56), the maximum computed rate of energy passing into the upper compartment as a result of heat conduction through an aluminum deck (i.e., excluding the development of openings), was 9000 kW; if water were applied to maintain air temperatures at or below 100°C, approximately 4 kg/s (60 gal/min) would be required, assuming 100 % application effectiveness.

8. CONCLUSIONS

This initial study demonstrated the potential value of computer modeling for deriving information on the important factors affecting fire growth and spread in Naval ship compartments. The basic configuration modeled was a compartment containing a single opening (vent) in one side which serves as the exhaust for hot gases at the top and as intake for outside air at the bottom. In this study, estimates of fire development have been provided over a very wide range of conditions.

Changes in geometric parameters (compartment size, vent size and location, etc.) result in non-linear changes in fire growth response due in part to the interacting effects of oxygen consumption, fluid flow and heat transfer. Under

Table 1. Material Thermal Properties

Material	Thickness mm	Thickness in	Density kg/m^3	Thermal Conductivity W/m K	Specific Heat J/kg K
Steel	9.4	3/8	7850	60	500
Aluminum (alloy)	6.3	1/4	2700	200	900
Thermal Insulation ("Kaowool")	25.4	1	64	0.072	1090
Cable Insulation (PVC)	10	3/8	1300	0.15	1000
Contents A (Polyurethane Foam)	-	-	48	0.054	1900
Contents B (PVC Cable)	-	-	1300	0.15	1000

Table 2. Estimated Hot Surface Ignition and Self-ignition Temperatures and Times

	T_{ig} (°C) hot surface	Time (min) hot surface	T_{ig} (°C) self-ignition	Time (min) self-ignition
Wood Fiberboard	230	50		
	200	200		
Wood	280	30	230	30
	250	120	200	120
Flexible polyurethane foam	300	30	250	30
	250	120	200	120
PVC (cable) insulation	400	30	350	30
	350	120	300	120

Table 3. Selected Computer Simulation Runs and Data Summary

Run No.	Compartment size m	Wall material S=steel A=aluminum K=Kaowool	Vent size m	Combustible contents kg	Initial (max) burning radius m	Propellant energy MJ	Run length s	Mass fraction pyrolyzed %	Steady-state mass loss rate kg/s	Total energy available MJ	Energy released in compart. MJ	Ratio	Approximate steady-state value: upper layer temp. °C	Approximate steady-state value: Outside wall temp. °C	Approximate steady-state value: Heat flux through wall kW/m^2
37	9x9x3	S	8x2	4000	0.1(3.0)	1000[c]	1500	77	2.2	75600	-	-	1015	785	71
38	"	S	5x2	1000	0.1(3.0)	1000[c]	1000	100	1.8	19800	11400	.58	900	670	40
40	"	S	8x3	1000	0.1(3.0)	1000[c]	854	100	2.4	19800	16500	.84	1100	840	88
41C	"	K	8x2	1000	0.1(3.0)	-	730	100	3.1	18650	6370	.34	1460	220	3.4
42A	12x15x3	S	8x3	5000	1.0(7.5)	-	1000	100	8.7	93200	36200	.39	880	670	45
42B	"	S	8x3	5000	0.1(7.5)	-	1060[b]	98	8.7	93200	27600	.30	880	670	45
43A	"	S	2x3	5000	1.0(6.0)	-	1000[a]	10	-	93200	-	-	-	-	-
46A	4x5x3	A	0.65x1.65	200	0.1(2.5)	-	1000	86	0.28	3730	-	-	540	420	14
47	"	S	0.65x1.65	200	0.1(2.5)	-	600[b]	29	-	3730	-	-	-	-	-
48B	"	A	0.65x1.65	1000	0.1(2.5)	-	3600	92	0.29	18650	5420	.29	545	440	14
49C	12x15x3	S	8x3	5000	0.1(7.5)	1000[c]	160[b]	10	-	94400	-	-	-	-	-
52A	2.5x2.5x2.5	S	0.65x1.65	200	0.1(1.25)	-	1260[b]	55	0.11	3730	-	-	850	640	39
53	"	S	1.95x1.65	200	0.1(1.25)	-	600[b]	47	-	3730	-	-	-	-	-
55	12x15x3	S	2x3	5000	0.1(7.5)	1000[c]	1000	100	10.1	94400	3900	.041	290	210	2.8
56	"	A	8x3	5000	1.0(7.5)	-	1000	100	8.9	93200	27100	.29	900	690	49
58B	"	S	4x3	5000	0.1(7.5)	-	654[b]	17	-	93200	-	-	-	-	-
59	"	S	4x3	5000	0.1(7.5)	1000[c]	1050	100	11.1	94400	9500	.10	520	400	9
61A	9x9x3	S	8x2	1000	0.1(3.0)	-	1000	98	1.4	18650	18650	1.00	1080	830	85
65B	"	A	8x2	1000	0.1(3.0)	-	1200	100	1.4	18650	18600	1.00	1090	845	85
66	12x15x3	S	1x3	5000	0.1(7.5)	1000[c]	633[b]	85	10.1	94400	1450	.015	240	150	5
67A	"	S	2x3	5000	0.1(2.0)	1000[c]	4640	61	0.65	94400	-	-	705	530	24
67M	"	S	2x3	5000	0.1(1.0)	1000[c]	9370[b]	37	0.20	94400	-	-	400	290	5

[a] Run terminated manually
[b] Run terminated automatically by program numerics
[c] Nominal; actual = 1150 MJ

Table 4. Estimated Time to Reach End-point Criteria

Run	Wall Material	Compartment Size m	Vent Size m	Combustible Contents kg	Time (min) Aluminum Melting	Loss of Strength	Hot Surface Ignition	Hot Air Ignition
56	Aluminum	12x15x3	8x3	5000	4	3	4	7
59	Steel	12x15x3	4x3	5000 +1000 MJ	NA	NA	18	60
65B	Aluminum	9x9x3	8x2	1000	7	6	7	4
48B	Aluminum	4x5x3	0.65x1.65	1000	NR	12	24	32

NA = not applicable
NR = not reached

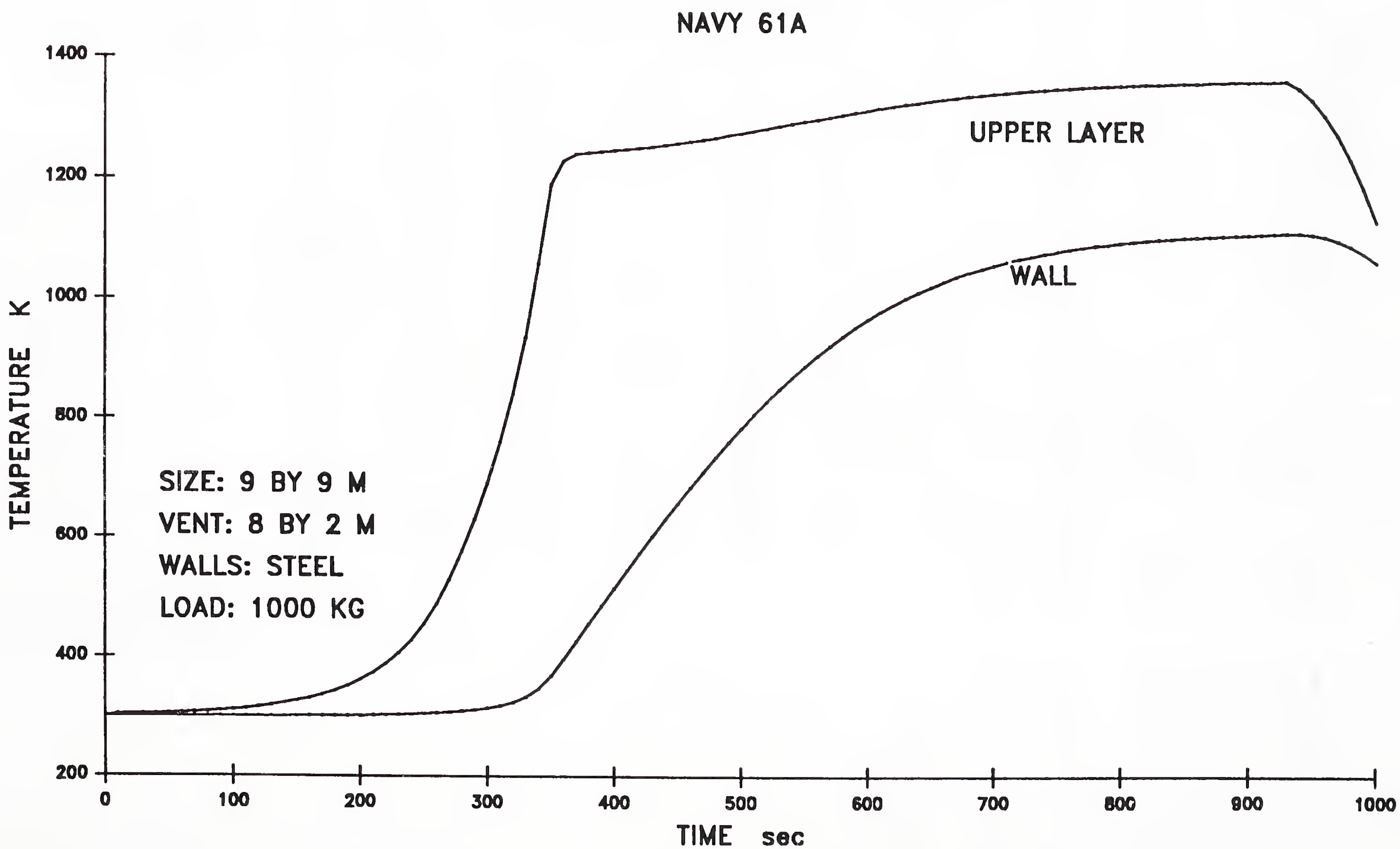

Figure 1A. Temperatures in steel compartment

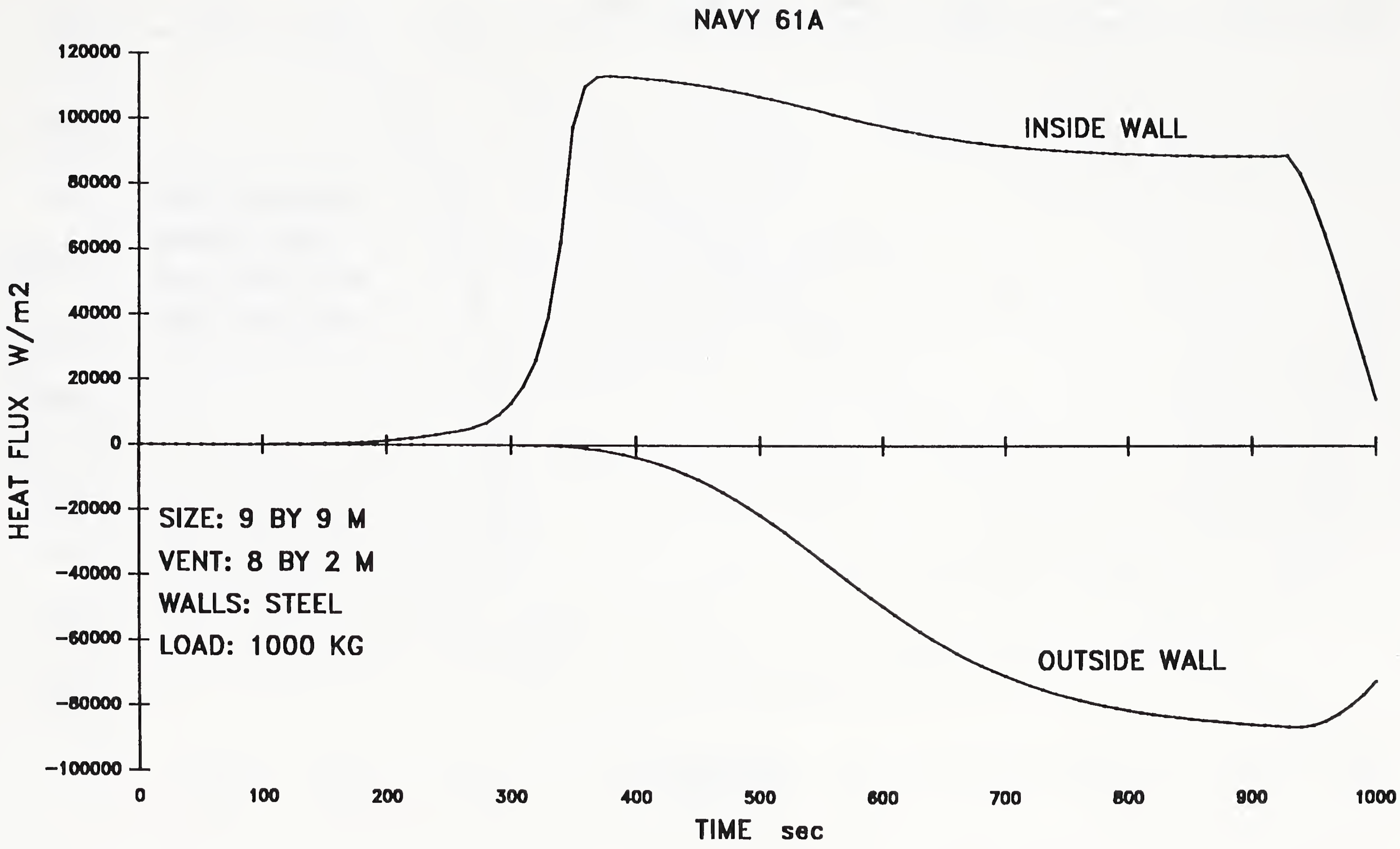

Figure 1B. Heat flux through walls

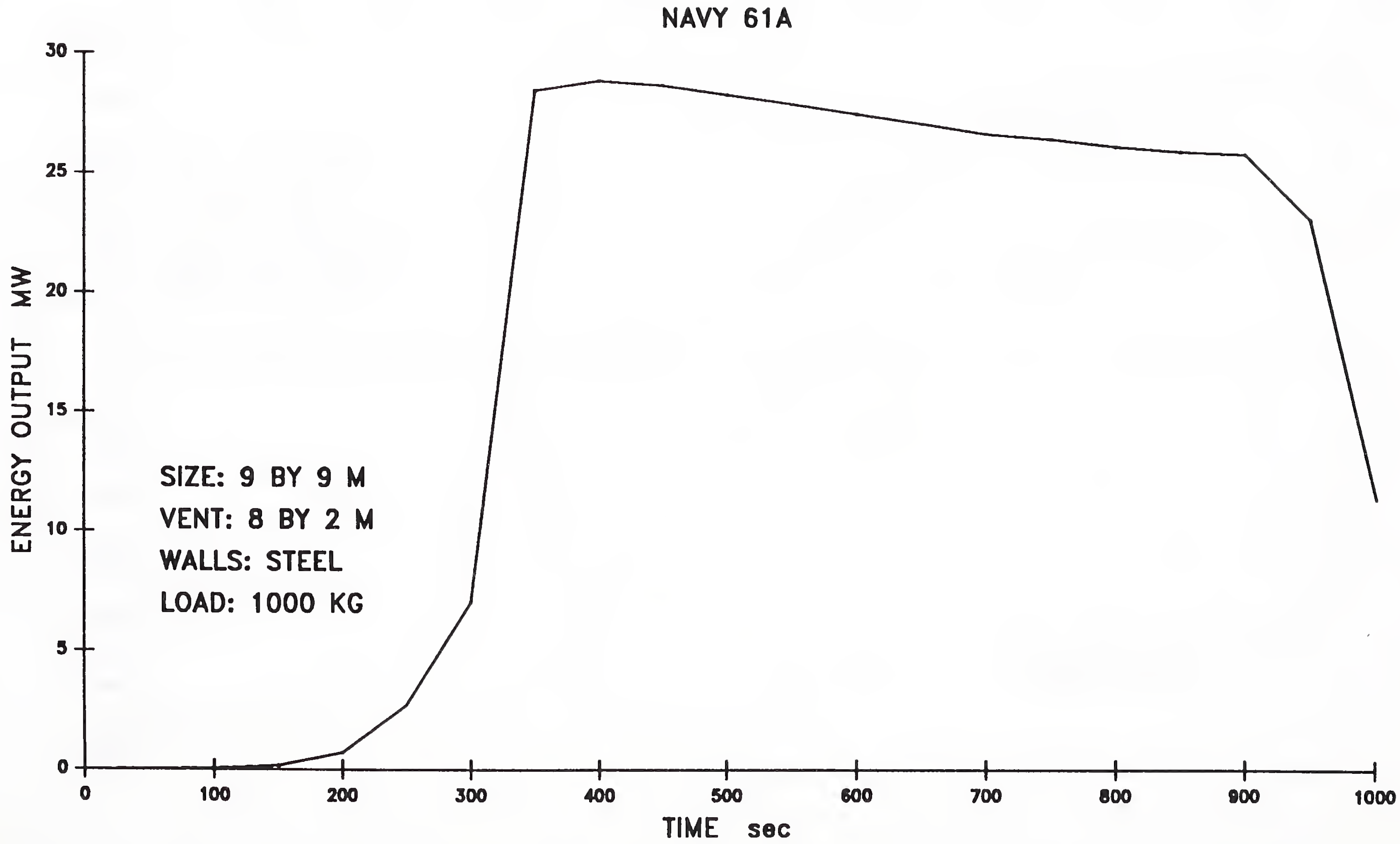

Figure 1C. Energy output from burning contents

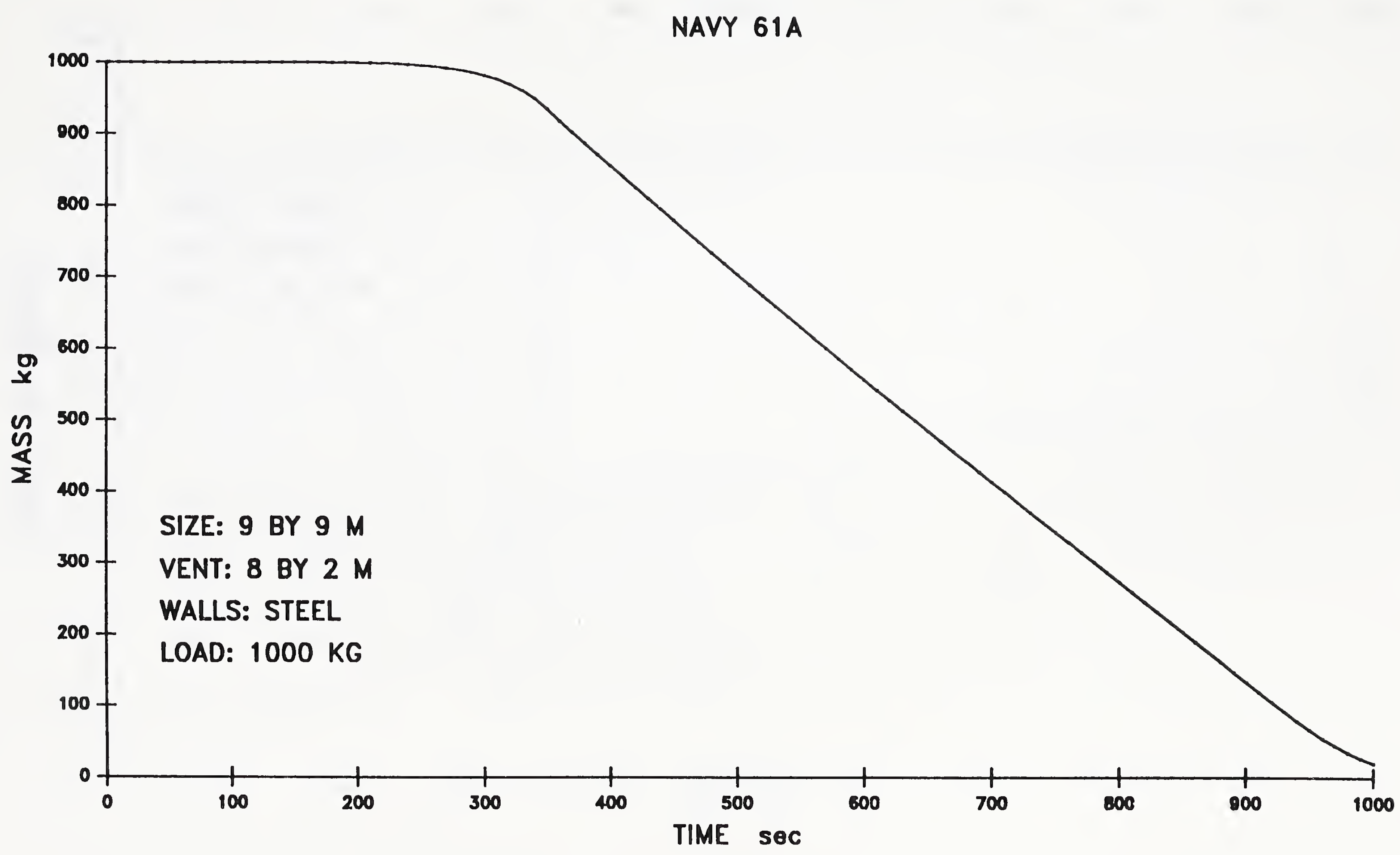

Figure 1D. Mass loss of contents

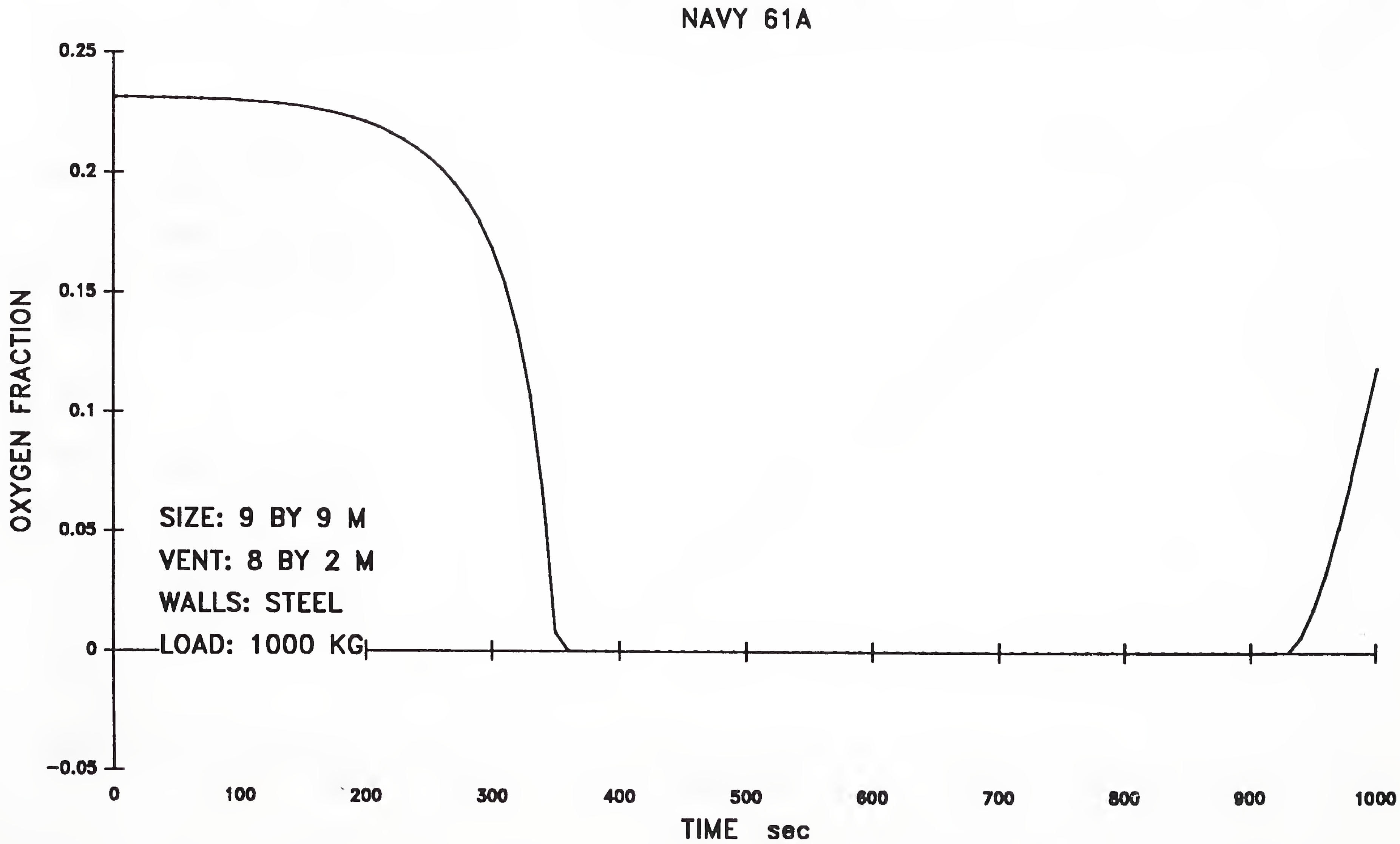

Figure 1E. Oxygen fraction in upper layer

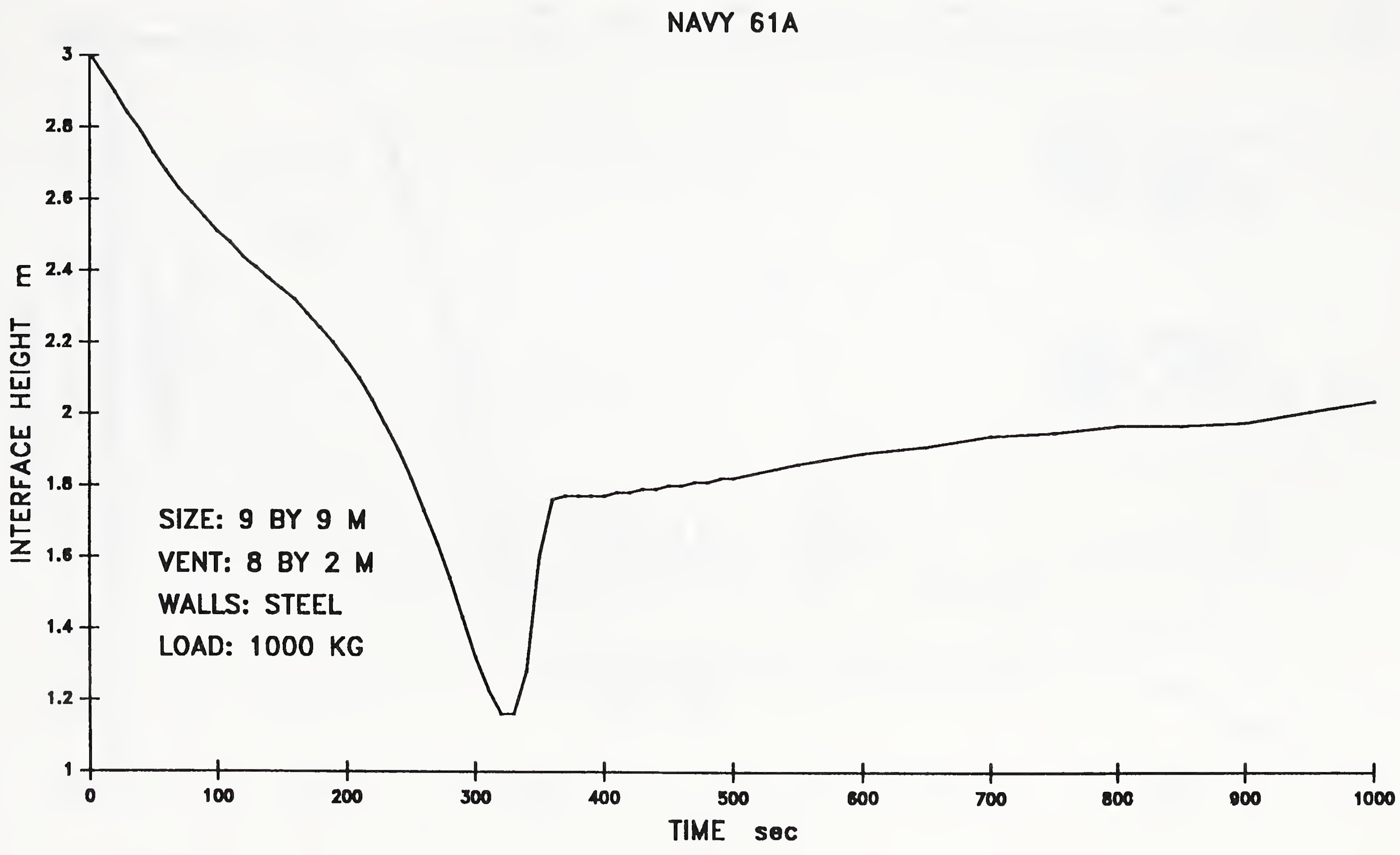

Figure 1F. Hot layer interface height

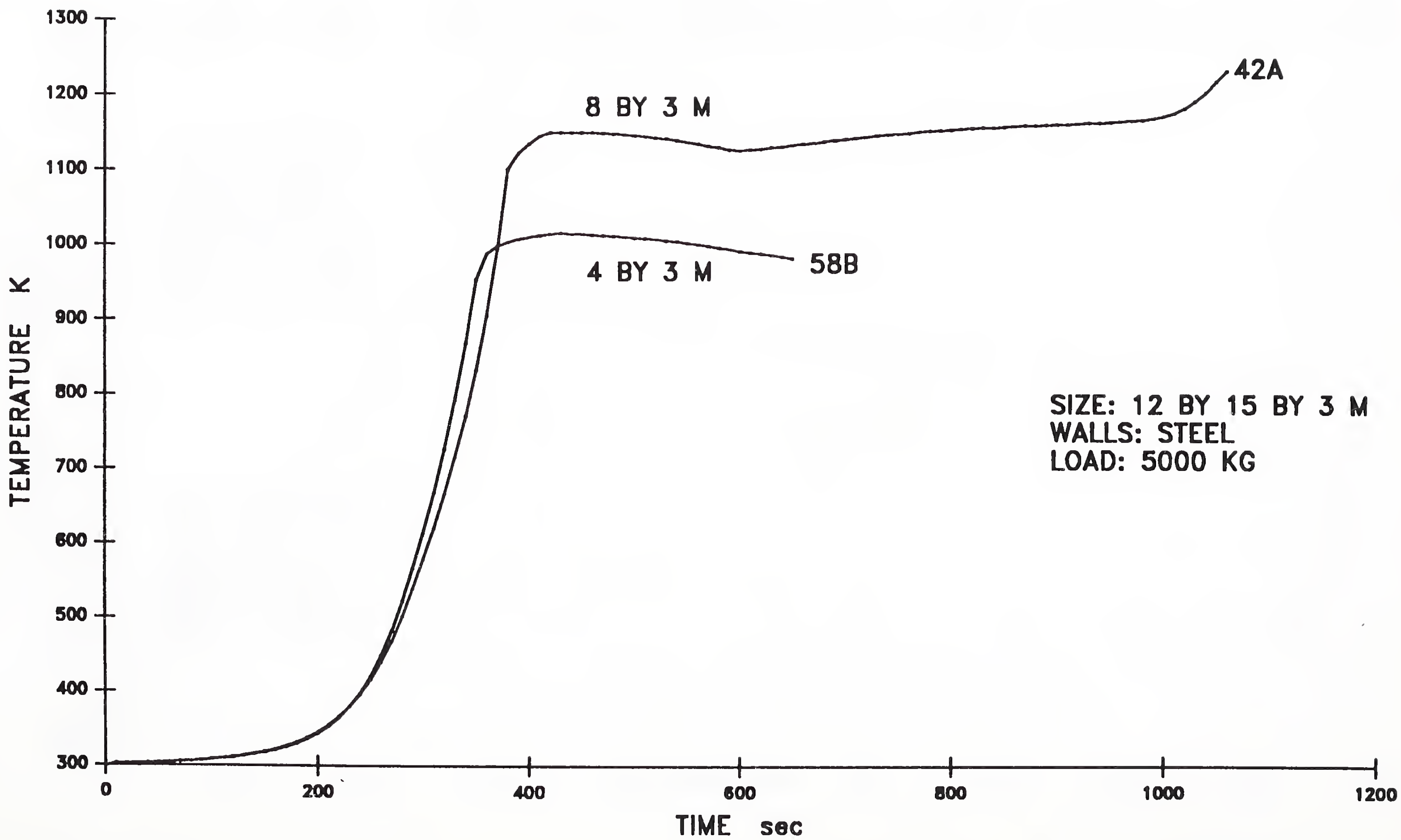

Figure 2. Effect of vent size on upper layer temperature in 12 x 15 x 3 m steel compartment without missile

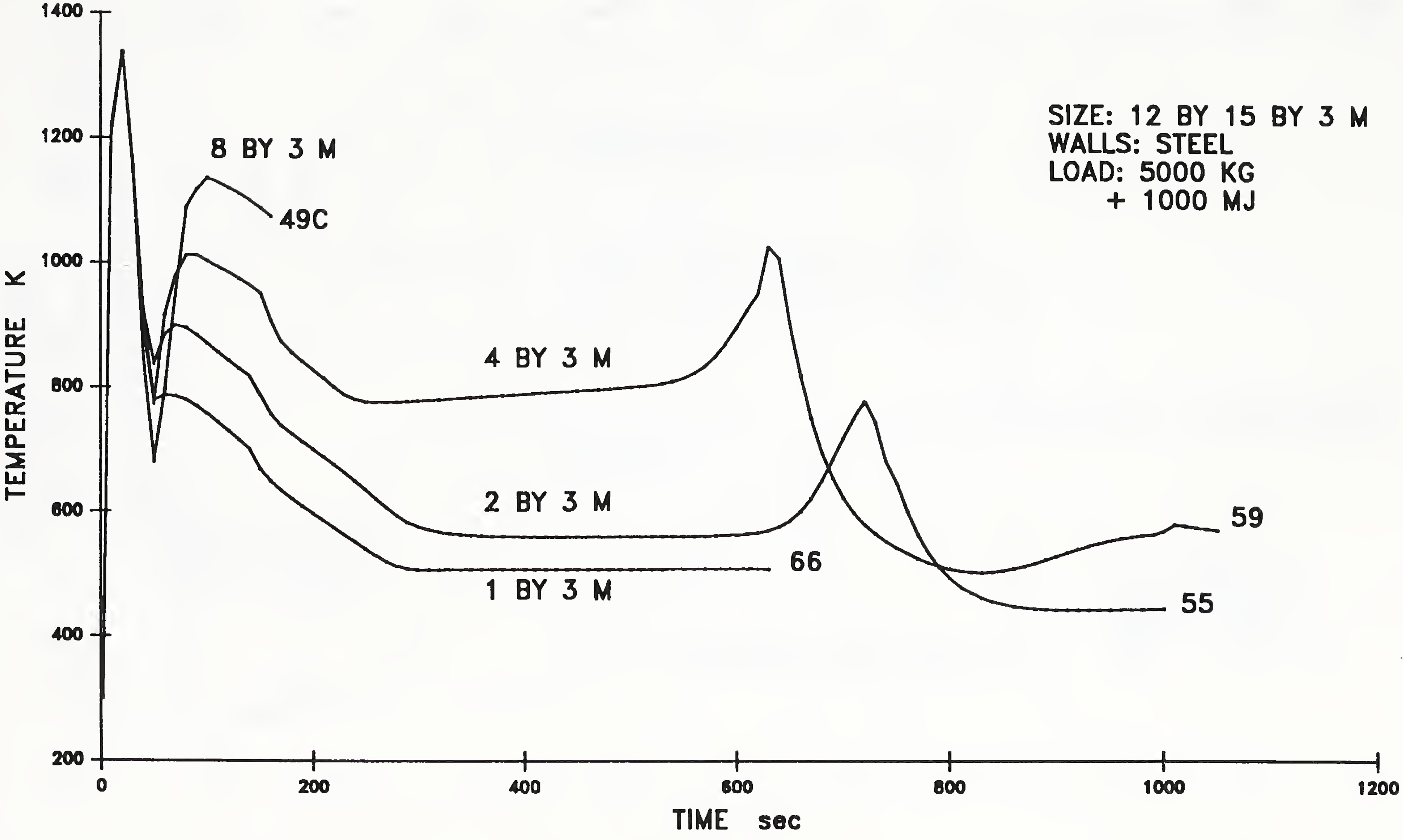

Figure 3. Effect of vent size on upper layer temperature in steel compartment with 1000 MJ missile

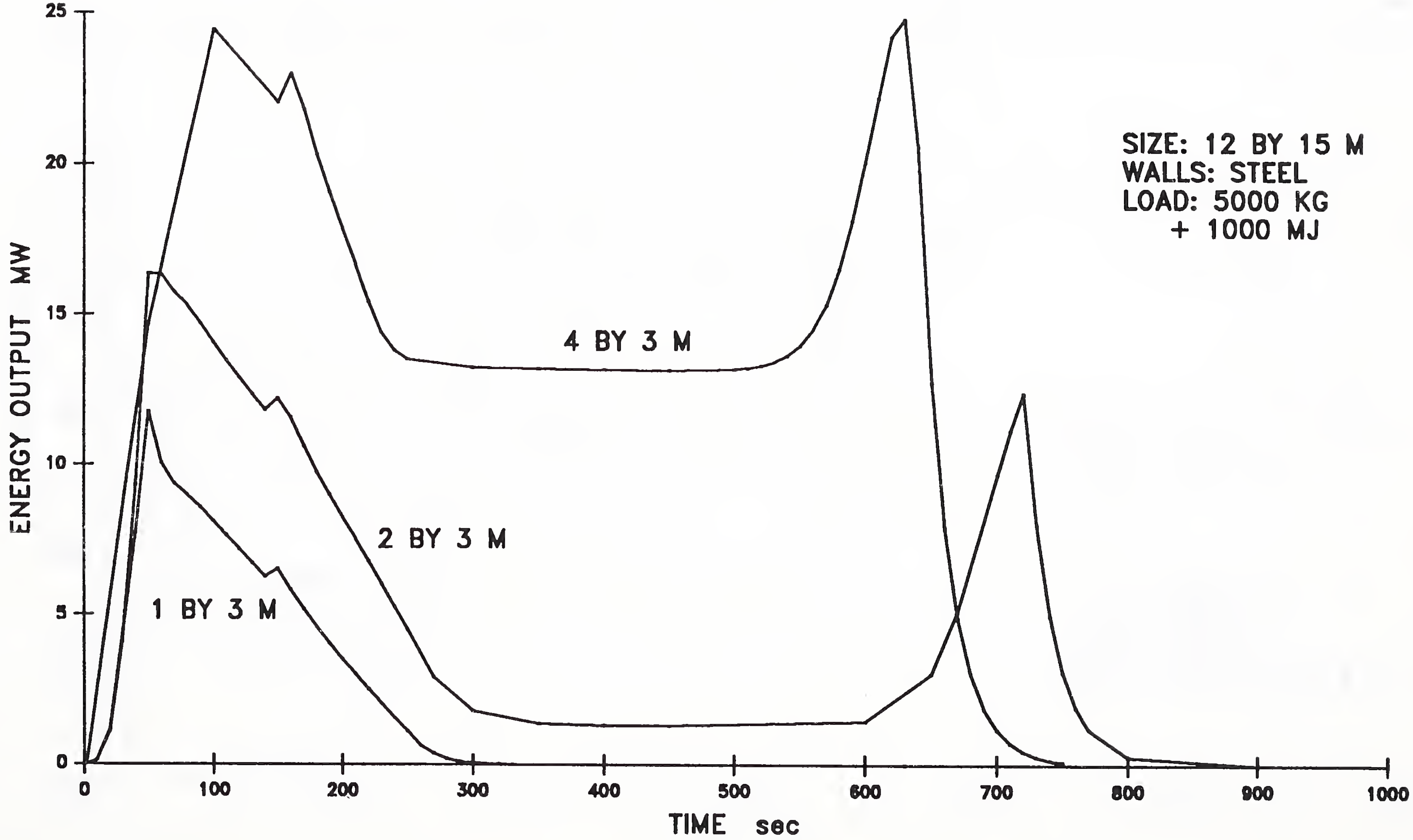

Figure 4. Effect of vent size on energy released from burning contents in steel compartment

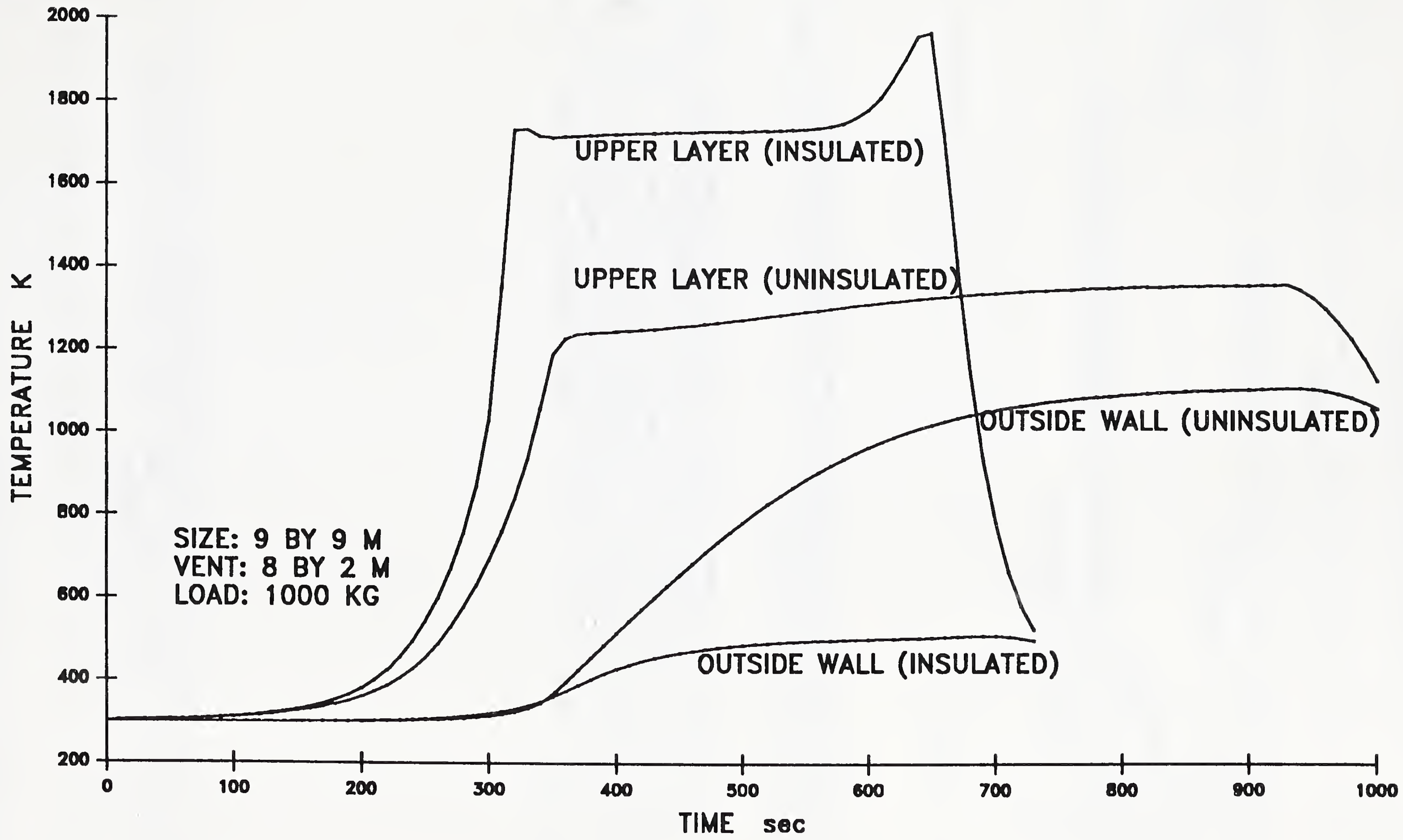

Figure 5. Effect of insulation (25 mm Kaowool) on temperatures in 9 x 9 m steel compartment

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This is a report to sponsor summarizing work accomplished under Naval Research Laboratory Contract N0017388WR80284 "Burning Characteristics of Combat Ship Compartments and Vertical Fire Spread." The computer program FIRST was employed to estimate levels of temperature, energy and heat transfer in burning compartments having features typical of Naval vessels with emphasis on vertical fire spread due to heat transfer through metal decks.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Aluminum deck; computer modeling; FIRST; missile propellant; self-ignition; steel deck; vertical fire spread

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